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Changes in moisture content and compression strength during storage of ventilated corrugated packaging used for handling apples

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Abstract: This study investigated the effects of cold storage (–0.5°C at 90% RH) on the mechanical performance of 'MK4' ventilated packaging used for handling pome fruit. The packages were stored over a period of 43 days. Compression strength of packages was measured by Lansmont squeezer compression testing machine on day 2, 4, 6 and 8 and then weekly over 6 weeks. The effect of storage duration on package moisture content and compression strength was also examined. Maximum compressive strength was reduced from 7351 to 3872 N after 2 days of storage. The package compressive strength decreased with an increase in moisture content. Average compression strength was observed to decrease by 618 N per one percent increase in moisture content. Pseudo first order kinetic model could satisfactorily analyse the adsorption of water by corrugated package with coefficient of determination of 0.9816 and standard error of 0.2554. Relationship between package compression strength with change in moisture during storage showed good correlation.

Keywords: Corrugated packaging; Compression strength; Vent area; Moisture content

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1 Introduction

Packaging is one of the most important steps in the long and complicated journey of fresh horticultural produce from grower to consumer. Venting, which is necessary for precooling and proper air circulation, also has the effect of decreasing mechanical strength of the package. Corrugated paperboard strength is an important requirement to protect produce against damage during storage and transport [1, 2]. The structural performance of a corrugated package is an important shipping requirement and has changed the paperboard market from one based on tonnage to one based on performance [3]. Box compression strength (BCT) commonly measure the performance potential of a corrugated board package [4].

Many researchers reported that corrugated paperboard is sensitive to the environmental conditions, such as high relative humidity [5–9]. Mechanical properties of corrugated paperboard are susceptible to temperature and relative humidity variation during the manufacturing, storage and distribution [10] Compression strength of a corrugated package in a given environment depends on the moisture content due to hysteresis in the absorption/desorption curve [11]. The increase in moisture content in the material breaks the bonds between cellulose fibres, affecting the mechanical behaviour and leading to subsequent failure load of the material [5]. Wetness due to high humidity storage reduces the compression strength of corrugated paperboard packaging. The strength reduction can lead to packaging collapse and mechanical damage to produce [12]. Furthermore, wetting of the cardboard may lead to biodeterioration of the package [13]. Box strength requirement and the influence of environmental exposure on the package performance must be considered when designing corrugated package for long term storage of fresh horticultural produce [14].

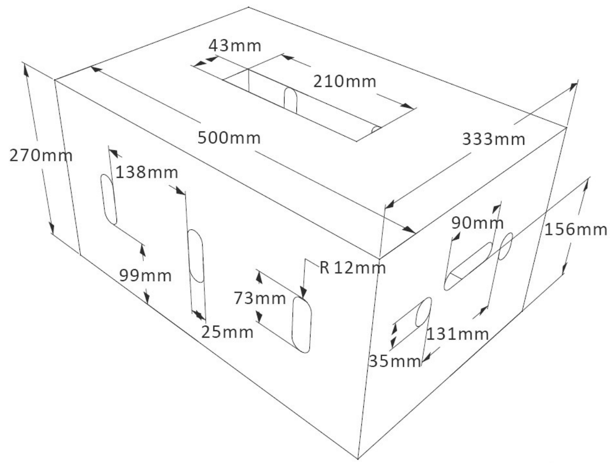

Figure 1: Ventilated corrugated packaging design (MK4) studied.

Fresh horticultural produce is subject to palletizing, cold storage and transportation, and hence the package must exhibit high stacking strength, resistance to moisture and withstand frequent changes in humidity [15]. Low temperature and high humidity are recommended to maintain quality of fresh horticultural produce [16]. Corrugated boxes stored under high humidity environments reduce their strength after absorbing moisture. Moisture is especially important when loading occurs over long periods as corrugated packaging sometimes fails during transportation and storage. Ventilated corrugated package should be designed to withstand mechanical stresses during distribution process. For engineering purposes, therefore, it is important to be able to determine the allowable load that does not cause collapse within the foreseen storage time. A number of researchers have studied airflow as well as the heat and mass transfer characteristics of ventilated packing systems [17–21], however very limited studies were found on package compression strength of ventilated corrugated packaging. In this study, the mechanical strength of 'MK4' corrugated packaging designs used in the pome fruit industry was investigated under compression load at storage conditions (−0.5°C at 90% RH). Effect of storage conditions on moisture content of package was also studied.

2 Materials and methods

Ventilated corrugated package, 'MK4', was used in this study (Figure 1). The package had dimensions of 500 (L) × 333 (W) × 270 (H) mm and carrying capacity of 18 kg. The corrugated paperboard for MK4 is a single wall of type 'C' flute. The corrugated paperboard used is made from Kraft paper with a paper grammage of 250 gm^{-2} for both inner and outer liners and a paper grammage of 175 gm^{-2} for the flute (corrugated medium). The package has open areas along the length and width, which were 3.8% and 3.5%, respectively, while both the top and bottom sections had vent areas of 5.4%.

'MK4' package design was conditioned at 23 ± 1°C and 50% relative humidity for 48 hours prior to testing in accordance with ASTM D4332. The packages were stored under the storage condition temperatures (−0.5°C and 90% RH) over a period of 43 days. Compression strength of packages was first measured on days 2, 4, 6 and 8 and then weekly over 6 weeks. All compression tests were conducted using a Lansmont squeezer compression test system (Lansmont Corporation, Monterey, CA, USA). A preload of 222.2 N was applied prior to observing the compression strength values. The floating-platen mode of the compression tester was used to conduct all testing at a speed of 12.7 ± 2.5 mm/min until failure was observed. Box compression test (BCT) is a pure top-to-bottom compression load test between flat parallel steel plates that is carried out on an empty sealed corrugated board box using a constant deformation speed [22]. The compressive load and crosshead displacement are recorded continuously until collapse occurs. Five different boxes were tested and the average values used for calculations. The moisture content was determined by the method of oven drying at temperature of 105°C (TAPPI T412) to constant weight.

Data analysis was performed using Microsoft Windows Excel 2007 and SAS 9.2 software (SAS, North Carolina, USA). Bonferroni comparisons were completed on the replicated data ($\alpha = 0.05$) in all tests.

3 Result and discussion

3.1 Variation in moisture content and strength with storage duration

Average moisture content at 23°C and 50% RH is 5.05% db (g water/g dry matter) for MK4 packaging. The moisture content of MK4 package exposed to storage condition (−0.5°C and 90% RH) over a storage period of 43 days is shown in Figure 2. Storage period from day 2 to 43 days showed the non significant effect ($P < 0.05$) on moisture content for 'MK4' packages. During that time, the moisture content increased by 61 – 118% compared to standard ASTM storage condition. Corrugated package

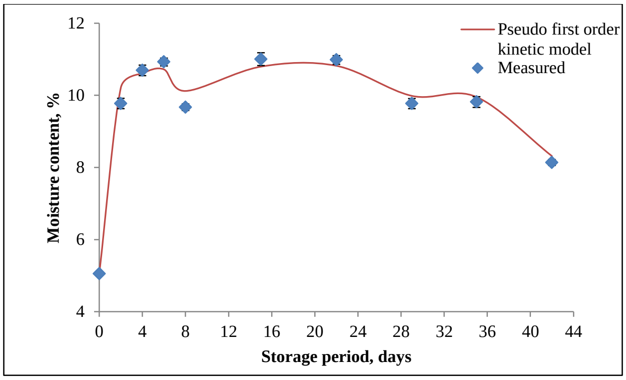

Figure 2: Moisture content of the corrugated package. Solid lines are fitted values. Bars represent standard error of the means (n = 5).

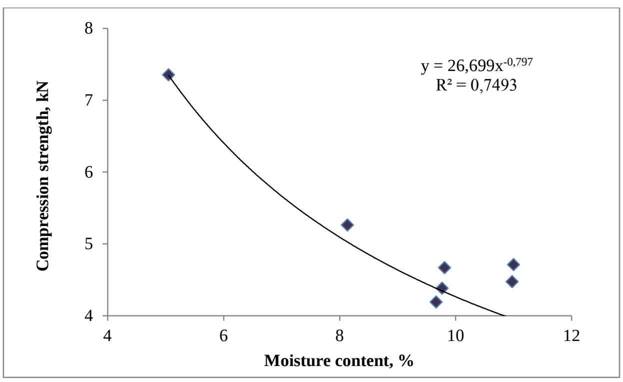

Figure 3: Relationship between moisture content and maximum compressive strength of corrugated package. Solid curves are fitted values (n = 5).

adsorbed water and moisture content increased with high humidity storage.

Pseudo first order kinetic model was used to analyse the adsorption of water by corrugated package. This equation has been used for water adsorption of brown rice [23], corrugated cardboard [6].

$$\frac{dM}{dt} = k_1 (M_e - M) \tag{1}$$

where k_1 is the rate constant of pseudo first-order adsorption (day^{-1}) calculated as 0.0192, and M_e and M are the moisture content (%db) at equilibrium and at time t (day). The method described by Jain and Pathare [24] was used to determine the equilibrium moisture content. After definite integration by applying the initial conditions ($t = 0$, $M = M_o$), Eq. (1) becomes

$$M = M_e + (M_0 - M_e) \exp(-k_1 t) \tag{2}$$

where M_o is the initial moisture content. The result in Figure 2 presents moisture content of corrugated package exposed to storage condition. Water absorption increased with time until it reached saturation. The data obtained from the pseudo first-order Eq. (2) was represented by a solid line. These expressions can be used to estimate the moisture content at any time with respect to the storage days with the greater accuracy. The established model was validated with experimental values of moisture content for all the tests of experiment. The linear regression of these results gave the following expression as

$$M_{pre} = 0.9681 M_{exp} + 0.3821 \tag{3}$$
$$\left(\mathrm{R}^2 = 0.9816,\ \mathrm{e}_s = 0.2554\right)$$

where $M,_{pre}$ and $M,_{exp}$ are the predicted and measured moisture content of corrugated package, respectively.

Eq. (4) represented the relationship between moisture content and maximum compressive strength [6] is as

$$F = aM^b \tag{4}$$

where F is compressive strength (kN) and the constant calculated as $a = 26.699$, $b = -0.797$. Maximum compressive strength of corrugated package was strongly dependent upon the moisture content (Figure 3). The maximum compressive strength of corrugated package was predicted using Eq. (5) which was obtained from Eqs. (2–4).

$$F = a[M_e + (M_0 - M_e) \exp(-k_1 t)]^b \tag{5}$$

Eq. (6) can be used to estimate the compression strength of package at any time with respect to the storage days with the greater accuracy.

$$F_{pre} = 0.8466 F_{expt} + 0.6474 \tag{6}$$
$$\left(\mathrm{R}^2 = 0.8519,\ \mathrm{e}_s = 0.4553\right)$$

where F_{pre} and F_{exp} are the predicted and measured compression strength of corrugated package, respectively.

3.2 Effect of storage duration on package strength

Storage duration has the influence on package compression strength. Mean compression strength of ‘MK4’ package designs at storage condition is shown in Figure 4. ‘MK4’ packaging shows the highest compression strength (7351 N) at standard testing condition. Figure 5 compared the compressive strength of ‘MK4’ packages exposed to storage conditions for 43 days. It showed the strength reduction between 28 to 53% at different storage periods. The packaging strength reduces from 7351 to 3872 N after 2 day

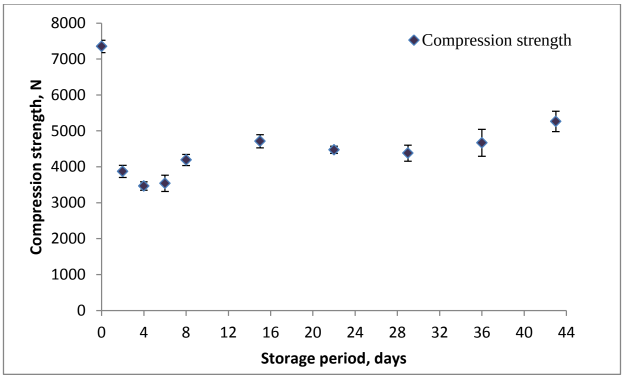

Figure 4: Mean compression strength of package during cold storage (−0.5°C and 90% RH).

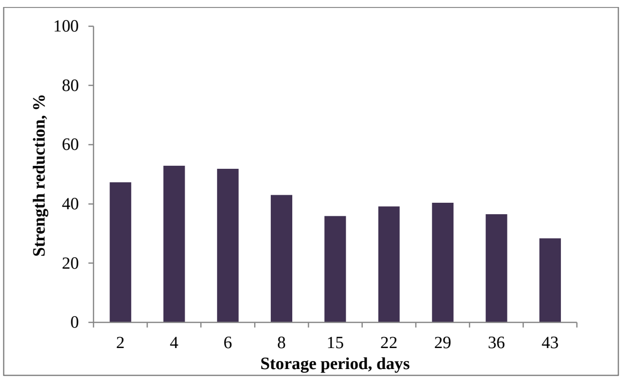

Figure 5: Package compression strength retained at storage condition (−0.5°C and 90% RH) compared to testing under standard (ASTM) condition (23°C and 50% RH).

storage period. However packaging strength changed from 3464.2 to 5261.9 N during from day 4 to 43 days.

Mean compressive strength of MK4 package exposed to storage condition (−0.5°C and 90% RH) decreased gradually over the time. From our experiments the moisture content of the package increased to 11% and maintained its maximum compressive load at 64.1% of 'MK4' package. After 43 days storage the package showed moisture content 8.14% and its maximum compressive strength reduced to 28.4%. BCT is a function of moisture content as compression strength distinctly decreases with the ascending of moisture content. Twede and Selke [7] reported that a box had lost its compression strength by about 40% at 85% RH. As the RH increased to 90%, the box was lost nearly 50% of its compression strength. Evidence was shown from our experiments that when the package was exposed to 90% humidity, the moisture content of the board remained at approximately 8.14% and maintained its maximum compressive load at 71.6% after 43 days.

Maximum strength reduction was found for the 2 day storage period (1739.1 N/day). After 2 days of storage, the moisture content of the package increased to 9.77% and maintained its maximum compressive strength at 52.7%. As corrugated package moisture content increased from 7.7% to 16.4%, compressive strength reduced by 52% [25]. Storage condition from standard testing to cold storage (day 2) shows significant influence on package compression strength ($P < 0.05$). However, the effect of storage period at day 2 to day 43 on compression strength was non significant. The influence of moisture content should be concerned when predicting the strength of corrugated packaging. The main impact of package design on optimisation of the fresh produce is to maintain mechanical integrity and improve cooling performance. An optimal package design with respect to mechanical integrity is not necessarily the best with respect to cooling performance and fruit quality.

Average compression strength decreased 618 N per moisture content percent from standard storage condition to −0.5°C and 95% RH storage. However maximum compression strength (737 N) decrease per moisture content was for early two day storage. As the increasing moisture content of the components have softened the lignin matrix between the cellulose microfibrils of the wood fibres and affects its mechanical property [1]. Moisture content of package during storage period (day 2 to 43) had non significant influence on package compression strength ($P < 0.05$). Average 'MK4' package had lost 8.4% strength per moisture content throughout the storage period. Typically a 1% change in moisture causes a 7% to 10% reduction in strength [11].

3.3 Effect on package deformation

Package deformation is a measure of how much a box is compressed at the end of a compression test [22]. Compression strength values of packages commonly include the deflection at failure or at the end of a specific load application. Under compression testing corrugated packaging displays buckling after deformation. Package deformation under storage period is shown in Figure 6. 'MK4' package designs showed the deformation 1.28 cm for maximum compression strength at standard ASTM testing. Storage duration had non significant influence on package deformation ($P < 0.05$). In the range of 8-11% moisture content of the packages tested under the investigated storage conditions, the displacement was in the range of 1.28 to 1.41 cm. In the current work, the displacement was not significantly ($P < 0.05$) affected by the moisture content of the package (Figure 7). This finding is in agreement with Paunonen and Gregersen [26] who studied the effect of

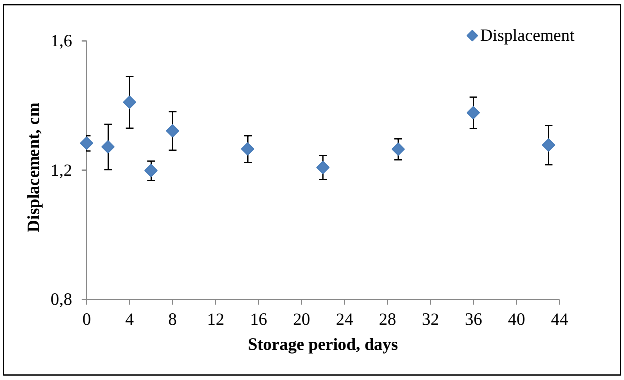

Figure 6: Changes in displacement of packaging at maximum compression strength during cold storage (−0.5°C and 90% RH).

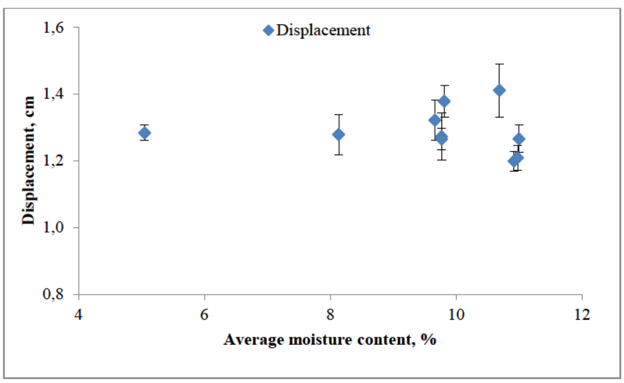

Figure 7: Effect of moisture content on displacement of packaging at maximum compression strength.

moisture content (range of 2% – 11%) on deformation and found that the displacement was constant (10 mm). The authors concluded that failure criterion for corrugated packaging in compression can be based on vertical displacement, and this is independent of moisture content.

4 Conclusions

In this investigation, the effects of storage duration on the moisture content and compression strength of 'MK4' package design used in the pome fruit industry were investigated. Pseudo first order kinetic model was used to predict the moisture content of package during storage period, providing a reasonable approximation. Package compression strength reduced with increase in moisture content. Maximum compression strength was reduced by 47.3% after 2 day storage. Maximum deformation did not depend on moisture content of the packaging material. This research can be of great help to corrugated packaging designers and handlers of various types of fresh horticultural produce at cold storage and transportation to preserve the strength of corrugated package, thereby ensuring a good quality product to the final consumers.

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